CONSTRUCTION AND TESTING OF SMALL-SCALE THERMOACOUSTIC ELECTRICITY GENERATOR WITH DIFFERENT HEATING POWER

by

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The necessity of renewable energy is indispensable. Nowadays, researchers focus on converting waste or solar heat into advantageous energy, such as electric energy, using thermoacoustic scientific knowledge. The thermoacoustic machine converts the heat energy into sound energy and conversely. Then, using a linear alternator, it converts into electric energy. In this study, we focus on the construction and testing of small-scale thermoacoustic electricity generators with different heating temperatures. The heat is converted into acoustic energy employing the thermoacoustic engine, and the acoustic energy is converted into electrical energy using the linear alternator. In this investigation, the heating power varies from 226-389 W. The result shows that 32.2 mW of electricity was found as the thermal power at 389 W. Moreover, the onset heating temperature span is 316 °C.

Key words: *thermoacoustic, engine, electricity, heating power*

Introduction

Energy consumption has rapidly increased due to technology development, rising population, and economic development [1]. These issues lead to the energy crisis in which the global demand on the limited natural mineral deposits used to power manufacturing companies and households is decreasing as the demand increases [2]. On the other hand, waste heat has become another environmental issue. Waste heat is often dissipated into the atmosphere or water like lakes, rivers, and the ocean. This increases GHG emission and contribute more to global warming [3]. The aforementioned issues can be solved using thermoacoustic technology. The waste heat can be transformed into sound energy, which can be used to drive the linear alternator to generate the electrical energy. Therefore, using thermoacoustic technology is good for the environment and renewable energy, especially electrical energy. Compared with the other technology, the thermoacoustic engine is pistonless so it will be easier and more applicable. Moreover, the improvement and accessibility of thermoacoustic refrigerators make them more effective and efficient than vapour compression refrigeration systems [4].

Thermoacoustic studies the interconnection between sound and heat with fluid and plate [5] and studies the transformation of heat to acoustic energy and conversely. Thermoacoustic can be divided into two types: thermoacoustic engine and thermoacoustic cooler. The

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thermoacoustic engine is a machine for converting thermal energy into acoustic energy [6]. Then, the acoustic energy can generate electric power using a linear alternator or turbine.

The thermoacoustic engine has been investigated by some researchers. Ueda and Farikhah [7], investigated the thermoacoustic energy conversion in the stack screen. They proposed a thermoacoustic numerical calculation method incorporating the empirical formula for the laminated wire mesh regenerator proposed by Obayashi *et al*. [8]. Using this method, the efficiency of energy conversion was numerically calculated in the laminated wire mesh regenerator of the thermoacoustic engine. The numerical results agree with the experimental results with an error of about 10%.

Furthermore, by comparing the energy conversion efficiency of the laminated wire mesh regenerator and the energy conversion efficiency of the regenerator with a uniform flow path, the effect of the complexity of the flow path on the efficiency can be clarified. Specifically, when the acoustic impedance is relatively low, and the temperature at the hot end is low, the flow path's complexity reduces the efficiency by nearly 40% [7]. This stack screen is usually used for the thermoacoustic engine. Other researchers focus on the effect of geometry on the efficiency of thermoacoustic [9-12]. Utami *et al*. [9] did the numerical simulation and found that the lowest heating temperature to generate spontaneous oscillation in the thermoacoustic engine is 124 °C when the narrow channel radius of the stack is 0.12 mm. The temperature is the low grade energy that can be utilized for waste heat recovery.

Moreover, the highest efficiency achieved as the flow channel radius stack equals 0.07 mm. Thus, the efficiency is 57% of the upper limit value [9]. Rokhmawati *et al.* [10] obtained the lowest initial heating temperature (15 °C) and optimal efficiency (38%) when the narrow radius of the engine stack is 5 cm and the mean pressure is 4 MPa. The effect of the regenerator length on the performance of the prime mover system was numerically studied. It was calculated numerically that the engine efficiency is 27% of the Carnot efficiency when the regenerator length corresponded to 6 cm [11]. Farikhah *et al.* [12] designed a 4-stage engine for waste heat recovery to find the best radii of the 4-stage thermoacoustic engine and obtain the low temperature for the engine. It was found that the low onset heating temperature is 43 °C and the total system performance is 8% of the upper limit value when all of the ratio of narrow engine radii to the thermal penetration depth is 1.2. Farikhah *et al*. [13] constructed the thermoacoustic cooler driven by a loudspeaker in 2013. Stem of goose down as an organic stack, a high thermal insulation material, was used for the plate media in the thermoacoustic engine. The goose down stack material has high thermal insulation, meaning it has low thermal conductivity of the plate media. There is no hazardous substance in the process, and piston is less. Air was used for the working gas, and stainless steel was used for the resonator. The decreasing cooling temperature is only 5 °C. This cooler can be driven by the thermoacoustic engine. Some researchers optimized the performance by changing some geometries. It was found that the performance was improved by some optimized parameters [14-18]. The influence of the stack's porosity on the performance of a thermoacoustic refrigerator driven by a thermoacoustic engine was conducted. The best porosity of the engine and cooler is 1.1, and the entire performance is 24% of the Carnot efficiency [14]. Liu *et al.* [15] did the numerical calculation on a thermoacoustic refrigerator. They found that the larger the column number of staggered parallel plates, the better the refrigeration effect will be obtained. Hakim *et al.* [19] studied the potential of electric power generation using mechanic vibration; however, the electric power is still low.

The challenge of the thermoacoustic is the advancement of thermoacoustic electric generators. The thermoacoustic electric generator is a combination between a thermoacoustic engine and an alternator-like loudspeaker which operates in reverse mode. It transforms heat energy into acoustic work and then into electric energy. Nowadays, the investigations on traveling wave type of thermoacoustic electricity generator have attracted some researchers due to their better efficiency but with a more complicated configuration. Therefore, in this research, we focus on the standing wave type of thermoacoustic electricity generator due to its simplicity. Ding *et al*. [20] and his group investigated thermoacoustic refrigeration systems driven by waste heat of industrial buildings. The cooling temperature achieved –12 °C and the cooling capacity is 0.95 kW. However, the configuration is more sophisticated [20].

Setiawan *et al*. [21, 22] and Murti *et al.* [23] investigated a thermoacoustic prime mover, but it did not apply to thermoacoustic electric power generation. Kitadani *et al.* [24] constructed the traveling-wave and standing-wave type thermoacoustic electricity generator employing a linear alternator to transform sound power to electricity and reach an electric power output of 1.1 W with a conversion efficiency from heat to electricity of 0.3%. Piccolo [25] studied a numerical simulation of thermoacoustic electric power employing a conventional linear alternator in a straight tube. The study results show that the acoustic-to-electric performance is about 70% when the heating temperature is 527 °C, whereas the thermal-to-electric conversion efficiency generated by the prime mover is 5.7%. Urip *et al*. [26] investigated pressure variation's influence on the initial temperature span and electric power output of a thermoacoustic electricity generator in a straight tube. It was found that the smallest onset heating temperature difference is 347 °C when the mean pressure is 0.35 MPa.

Moreover, 691 W of electrical power is achieved when the pressure is 0.40 MPa with 347 °C of onset temperature difference [26]. Moreover, the heating power used in this experiment is 370 W. In 2012, the traveling-wave thermoacoustic electricity generator using an ultra-compliant alternator was built and produced 11.6 W of electrical power. However, the device needed larger space, making the design more complex [27]. Wang *et al*. [28] performed the improvement of a 500 W thermoacoustic electric generator. They found a maximum electric power of 473.6 W at 2.48 MPa. It was found that the efficiency achieves 14.5%, but the onset heating temperature is quite high at 650 °C. A two-stage traveling-wave thermoacoustic electric generator was investigated. The study results show that 204 W of electric power is obtained, but the onset heating temperature is high at 597 °C and 511 °C [29]. The design and performance of a two-stage standing wave thermoacoustic electricity generator was investigated in 2016. Even though the electric power is high, the heating temperature of the engine is high [25]. Hamood *et al*. [30] designed and constructed a two-stage thermoacoustic electricity. However, the mean pressure is too high. A few researchers have investigated the influence of heating power on the onset heating temperature and electric power of a simple standing wave thermoacoustic generator. Therefore, we focus on it in this experimental study.

Experimental method

The investigation was conducted using an experimental research approach. First, a standing wave thermoacoustic power with a branch was constructed. Then, some measurements were conducted, and the results related to the onset heating temperature difference, electric power, pressure, and frequency were presented.

Construction

The schematic diagram of the thermoacoustic electric power generation with the branch used in this investigation is illustrated in fig. 1. The system comprises some components: thermoacoustic engine core and linear alternator. The thermoacoustic engine core is inserted into a pipe called a resonator. The resonator is made from stainless steel, and it is 29 cm

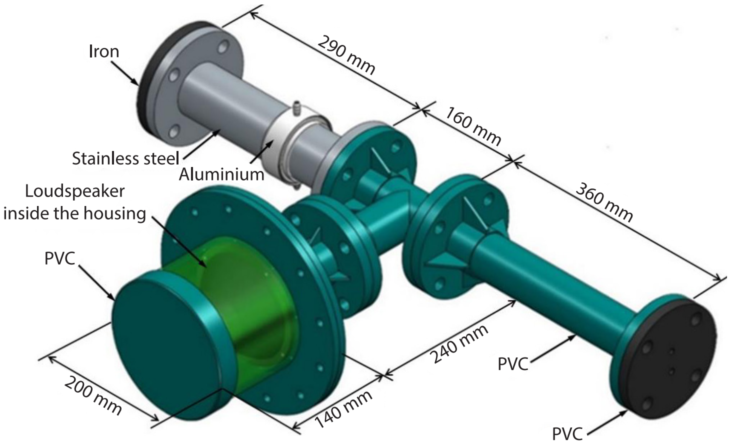

Figure 1. General design outline of a simple standing wave thermoacoustic electricity regenerator with branch

in length. It is connected to the resonator branch, where the loudspeaker is located. The length of the connecting pipe is 16 cm, while the branch pipe is 24 cm in length. The other part of the resonator, made of polyvinyl chloride (PVC), has 36 cm in length.

In the engine core part, the stack, hot, and ambient heat exchangers are installed in the first part of the resonator. The stack is sandwiched by the hot and ambient heat exchangers. The length of the heat exchangers is 4 cm, whereas the length of the stack is 3.5 cm. The stack is made of a stainless-steel wire mesh screen with mesh number 12, see fig. 2(c). The porosity of the stack, φ, is 0.814, while the wire diameter is 0.050 cm. Using the equation:

$$r_{\text{h}} \cong d_{\text{wire}} \left[\frac{\varphi}{4(1-\varphi)} \right]$$

the stack's hydraulic radius, r_{h}, is 0.0547 cm. This parameter shows the heat exchange process between the pore walls of the regenerator and the working fluid. The δ_{k} is the thermal penetration depth, and τ is the thermal relaxation time in the cross-section of the regenerator's channel. The value δ_{k} is 2.0 defined as thermal penetration depth, which means the gas layer space in which heat can pour over an interval of time. It can be expressed:

$$\delta_{\text{k}} = \sqrt{\frac{k}{\rho c_p \pi f}} \tag{2}$$

where k is the thermal conductivity, ρ – the density, c_p – the specific heat in the constant pressure, and f – the frequency. Those gas property values are shown in tab. 1.

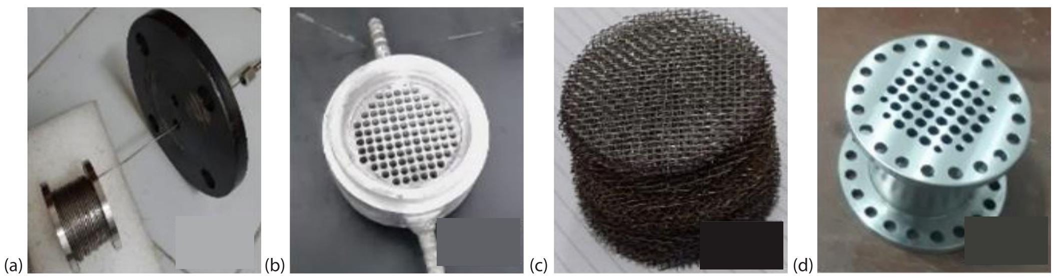

Figure 2. (a) heater, (b) hot heat exchanger (c) screemesh stack, and (d) ambient heat exchanger

Table 1. The module and *T/S* parameters of the loudspeaker

Specification		Parameter *Thiele-Small*	
Frame diameter [[inch or mm]	6 inch or 15.24 cm	Resonance frequency, *Fs* [Hz]	50 Hz
Impedance [Ω]	8 Ω	DCR [Ω]	5.0 Ω
Maximum power [Wa]	60 W	Q_{ts}	0.78
Wide of frequency area [Hz]	50 Hz-7.5 kHz	Q_{es}	0.99
SPL (2.83 V/1 m) [dB]	89 dB	Q_{ms}	3.59
Cone paper effective diameter [mm]	15.0 cm	M_{ms} [g]	12.3 g
Magnetic field [T]	1.15 T	C_{ms} [mmN^{-1}]	0.078 cm/ N
Weight of magnet [kg/Oz]	0.27 kg/9.50 Oz	BL product [Tm]	4.5 Tm
Voice coil diameter [mm]	2.54 cm	V_{as} [L]	20.4 Liters
Voice coil material [mm]	Asv	N_o [%]	0.27 %
		Sd [cm^2]	136.8 cm^2
IEC 268-5 (in box system, cut off 20-500 Hz)		X_{max} [cm]	0.24 cm

The ambient and hot heat exchanger length are 4 cm, while the diameter is 6.8 cm. The heat exchangers have tiny holes with a diameter of 0.3 cm, and it is parallel to the axis of the resonator that allow the working fluid to oscillate to the pores. The heat exchangers are made of copper, which isa good thermal conductivity.

Figure 2(a) shows the heater used for heating the hot side of the stack. The hot and ambient heat exchangers are shown in figs. 2(b) and 2(d). The heat exchangers have holes with a diameter of 0.3 cm, and it is parallel to the axis of the resonator, allowing the working fluid to vibrate to the tiny holes. The heat exchangers are made of copper, which is a good thermal conductivity.

The loudspeaker was employed as a linear alternator which converts acoustic into electric energy. It is located at the side branch, and it has 24 cm in length. The loudspeaker diameter is 15 cm, the impedance is 8 cap omega, and the loudspeaker terminals are connected to the resistor. The actual surface area of the loudspeaker cone is denoted as Sd, and it is 136.8 cm^2. The electrical power generated by the loudspeaker can be calculated using:

$$W_e = \frac{V_{rms}^2}{R_L} \tag{2}$$

where W_e is the electric power, V_{rms} – the root mean square voltage, and R_L – the load resistance. The input electric power was turned on as the temperature at the stack hot side has not elevated considerably. Therefore, the temperature span between the two sides of the stack remained constant. This system is assumed to be in a steady-state condition. The temperature pressure amplitude and the electric voltage output are stopped after the electric power input is turned off. This step was repeated for heat input 226-389 W.

The resonator used in the thermoacoustic engine part is 29 cm, while the connecting pipe is 16 cm. This pipe is connected to the other resonator, which is 36 cm in length, and the side branch where the loudspeaker was placed. The total length of the resonator is 81 cm. The resonance frequency of the closed resonator tube can be calculated:

$$f_n = \frac{nv}{2L} \tag{3}$$

where v is the speed of sound of the working fluid and L – the resonator length. The harmonic series frequency is denoted as f_n. The n is n^{th} harmonic series (n = 1, 2, 3,…). By using the sound speed in tab. 1 with a resonator length of 81 cm, the calculated resonant frequency with the heat input range of 226-389 W is around 212 Hz for the first harmony frequency (n = 1) and 424 Hz for the second harmony frequency (n = 2).

Table 2. The gas properties [32]

P_m	0.1 MPa
γ	1.4
ρ_m	0.52 kg/m^3
σ	0.707
C_p	1.0049 kJ/kgK
C_v	0.7178 kJ/kgK
c_s	348 m/s
K	0.026 W/mK

Table 2 shows the gas properties determined at 0.1 MPa of mean pressure, and air was used as the working fluid (gas) at 300 K [31]. The γ is the specific heat ratio, which is a dimensionless parameter C_p/C_v, where C_p and C_V are isobaric and isochoric specific heat, respectively. The σ is the Prandtl number of the working gas, which is also a dimensionless number ν/α, where ν and α are kinematic viscosity and thermal diffusivity, respectively. The P_m, ρ_m, c_s, and K are the mean pressure, density, sound speed, and thermal conductivity of the working fluid. The porosity shown in tab. 3 is the dimensionless parameter, which is defined as the ratio of open area in the cross-section the total cross-section area of the stack.

Table 3. Length and size

Total of the resonator length	81 cm
Length of stainless-steel resonator	29 cm
Length of connecting pipe	16 cm
Length of branch pipe	24 cm
Length of PVC Resonator	36 cm
Inner diameter of the pipe	5.5 cm
Length of stack	3.5 cm
Mesh number	12 strands/inch
Porosity of stack	0.814
Wire diameter	0.050 cm
Hydraulic radius	0.0547 cm
Length of ambient heat exchanger	4 .0 cm
Length of hot heat exchanger	6.8 cm
Diameter of small holes of heat exchanger	0.30 cm
Length of the linear alternator	2.4 cm
Diameter of the linear alternator	15.0 cm
Impedance	8.0 Ω

Measurement

To measure the temperature at the regenerator sides, T_a and T_b, the thermocouples were used. As the electric heater turns on, the thermocouples begin to record the temperature using the data logger. After the heat is imposed on the hot end of the regenerator, a spontaneous oscillation appears because of the temperature gradient on the thermoacoustic engine, and the sound wave is propagated. Then, the pressure *vs*. time can be measured using the pressure sensors, displayed by a WE7000 data logger software. Using fast Fourier transform (FFT), the time domain data was transformed into the frequency domain. Four pressure sensors were used. To measure the oscillation pressure, the transducers are installed along the resonator tube. The pressure was measured using Kyowa PGMC-A-200 KP with non-linearity and hysteresis within 1.34% RO and 0.12% RO, respectively. The temperature was measured using a K-type thermocouple with a special limit of error ±1.1 K. The measurement error E_m:

$$E_\mathrm{m} = \sqrt{E_\mathrm{s}^2 + E_\mathrm{r}^2} \tag{4}$$

and

$$E_\mathrm{r} = \frac{\sqrt{\sum_{i=1}^{n} \frac{\left(y_i - \bar{y}_i\right)^2}{n-1}}}{\sqrt{n}} \tag{5}$$

where R_r is the random error, E_s – the systematic error, n – the number of repeated measurements, and y_i – the arithmetic mean representing the y^th measurement [32]. Using eqs. (4) and (5), the pressure and temperature measurement error can be estimated to be ±4.00 Pa and ±3.00 K, respectively.

To measure the heating power, the electric heater was introduced. It is imposed at the hot heat exchanger. At the ambient heat exchanger, the cooling water was circulated to maintain the ambient temperature. By using a digital voltmeter (measuring voltage, V) and a digital ammeter (measuring current, I), input heating power can be calculated as $Q = VI$ (rms value).

In this investigation, the heating power was varied by the heater, and the acoustic power was generated inside the engine stack. Using some pressure sensors, the pressure can be measured, and acoustic power can be obtained. On the other hand, the temperature can be measured using and recorded in the data logger. The acoustic wave traveling is along the resonators and the side branch where the loudspeaker was located. In the loudspeaker, the acoustic energy was converted into the electric energy.

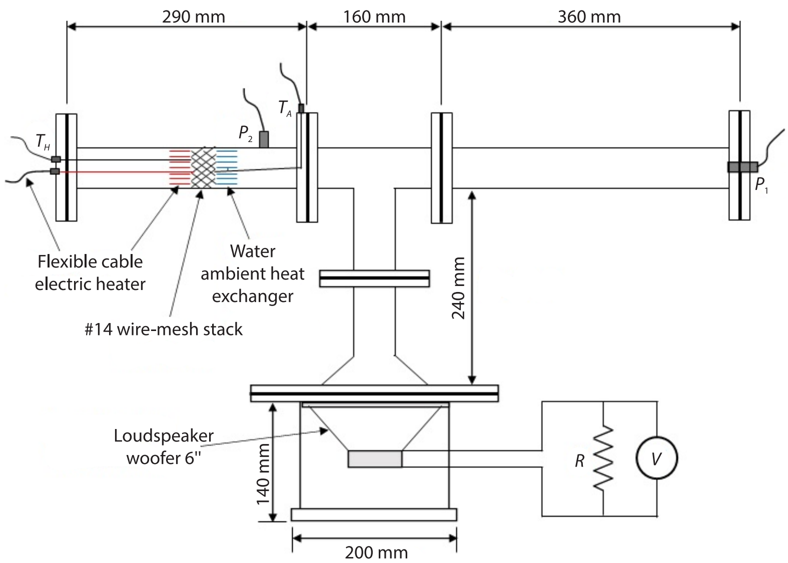

Figure 3. Experimental set-up of the thermoacoustic electricity generator with side branch configuration

The prototype of a small-scale thermoacoustic electricity generator with a side branch configuration was built. Figure 3 shows the experimental set-up. The system comprises a thermoacoustic engine, linear alternator, and resonator with branch. The engine regenerator is installed inside the resonator and is employed as the thermoacoustic engine. A loudspeaker was used for the Linear alternator to transform acoustic into electric power. In this investigation, the atmospheric pressure was used. The working fluid is air, and the heat power is input into the system. The ambient heat exchange is running on the tap water and is using a water tank. The rejected water is collected. The temperature in the hot and ambient side of the engine regenerator was measured by the E-type thermocouples, and the pressure transducers were obtained using data acquisition. It is connected to a data logger system. A power analyzer was employed to measure the current and voltage.

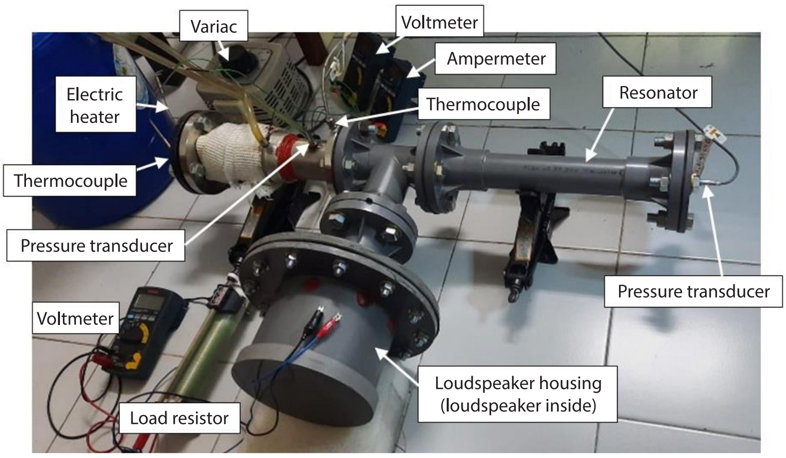

Figure 4. General arrangement of thermoacoustic electricity generator with side branch configuration

Working principle

Thermoacoustic electricity generator with side branch configuration comprises a resonator, a regenerator engine, a hot heat exchanger, an ambient heat exchanger, and a loudspeaker for the Linear alternator, see fig. 4. The regenerator was arranged from the stack wire meshes in which the thermoacoustic effect occurs. The regenerator and the heat exchangers were installed in the resonator. In the thermoacoustic engine, there are no moving parts to perform the thermodynamics cycle. The presence of the regenerator plate and the working fluid is essential for the engine. When the heat source imposes the engine regenerator, the gas particles on one side become hot. As shown in fig. 5, the gas particles experience four-step cycle: two constant pressure heat transfers in Steps 2 and 4 and two adiabatic in Steps 1 and 3.

Step 1 shows that the gas parcel experiences adiabatic compression while it displaces from the ambient side to the hot side. The fluid parcel is warmed. Then, in Step 2, it experiences the constant-pressure heat transfer from the plate to the gas parcel. After that, the gas parcel in Step 4 experiences adiabatic expansion, and it displaces from the hot side to the ambient side. In Step 4, the gas parcel experiences constant-pressure heat transfer from the parcel to the plate. In Step 2, the gas parcel experiences thermal expansion at high pressure, while in Step 4, it experiences thermal contraction. As a result, the acoustic work is generated, dW – dW'. In this case, the acoustic energy is generated in the engine regenerator [6]. The acoustic power generated in the thermoacoustic engine is delivered into the loudspeaker where the conversion of the acoustic power to the acoustic power occurs.

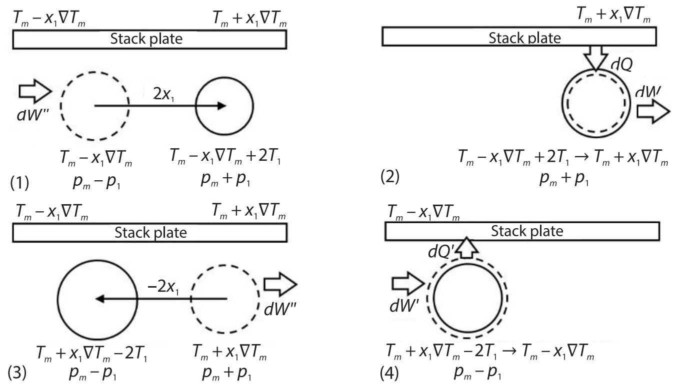

Figure 5. Typical fluid parcels occur in the stack [33]

Result and discussion

Figure 6(a) presents the result of measuring temperature as a function of time. This investigation used 0.1 MPa of air for the working gas. The red line shows the stack's hot side temperature, while the blue line presents the stack's ambient end temperature. Figure 6 shows that as the heater was turned on, the stack hot temperature rose considerably. On the other hand, the stack ambient temperature remained constant. The spontaneous oscillation was ex-cited when the onset heating temperature achieved a value. Then, the stack generated acoustic power. Figure 6(a) shows the thermocouple's readings throughout experiment, which took 60 minutes. A 219 Hz was the spontaneous oscillation at the onset heating temperature, T_h (344 °C) with 28 °C of ambient temperature, T_a. When the frequency is 219 Hz, the spontaneous oscillation occurs at the onset T_h (344 °C) with 28 °C of T_a. As a result, the onset heating temperature difference is 316 °C. Thermal energy was converted to acoustic energy. Meanwhile, the linear alternator produced about 33 mW of electric power.

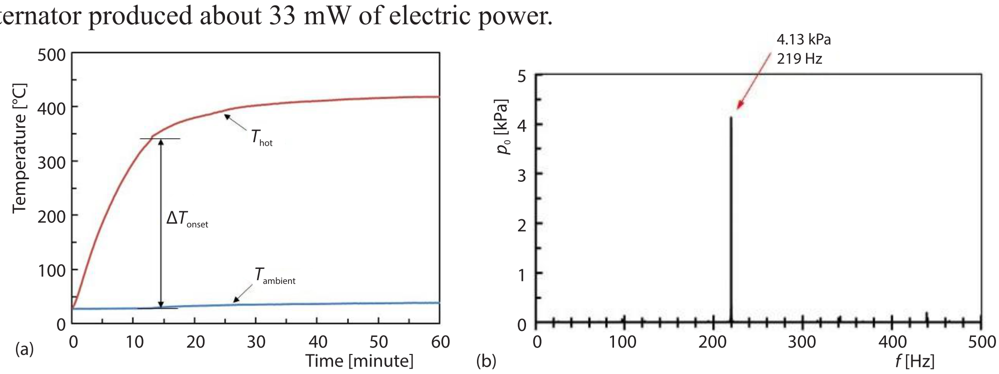

Figure 6. (a) Temperature *vs.* time over the testing period (60 minutes) and (b) the p_0 *vs.* f

The pressure transducer is installed along the resonator tube. The pressure oscillation was measured using a transducer. Then, employing FFT, the frequency of the sound waves can be generated. Figure 6(b) presents the frequency spectrum of the sound waves at 1 atmosphere. It was taken at resonant frequency. As we can see in fig. 6(b), the FFT analysis shows a dominant frequency of 219 Hz.

Figure 7 shows that the temperature difference occurs influenced by the heating power (besides being influenced by many factors). It can be seen that the onset temperature difference increases by approximately 2 °C from 314-316 °C when the heating power increases by 163 W from 226-389 W. This happens because the temperature increases on the hot side of the stack becomes faster when the heating power is greater. The onset heating temperature difference is 316 °C. Compared to that found by Tutur *et al*. [26], this temperature is lower. They found 347 °C which means 31 °C higher than that found in this investigation. One important thing is that the lowest heating power at 226 W, shown in fig. 7, is the minimum heating power needed so that the onset (thermoacoustic effect/sound generation) can occur. Heating power below 226 W cannot generate sound.

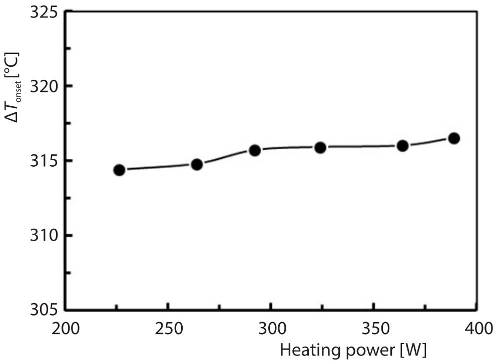

Figure 7. Heating power *vs.* ΔT_{onset}

Heating power as a function of onset temperature difference ΔT_{onset} is shown in fig. 7. When the heating power increases, the onset heating temperature difference rises from 314-316 °C. Figure 8(a) shows the experimental result of the frequency produced by the engine with different heating temperatures. It can be seen that the frequency slightly increases when the heat input increases. Figure 8(b) shows the effect of heating power on the pressure amplitude, p_1. It shows that the pressure amplitude increases from 2-5 kPa. The electric power generated by the loudspeaker in the steady-state is shown in fig. 9. When the heat input is 226 W, the electric power is 8 mW, but when the heat input is 389 W, the electric power is about 33 mW.

Air is the working fluid at 100 kPa. The r_h/δ_k has been calculated to be around 2.0. It means that thermal interaction between the working gas and the stack occurs effectively when the hydraulic radius of the pores of the stack is 2.0. The increase in ΔT_{onset} is the reason for the increase in frequency, f, p_1, and output electrical power, W_e.

Figure 8(a) shows that the frequency of the sound generated experiences a significant increase as the heating power increases. It increases by around 2.1 Hz, from 217.7-219.6 Hz when the heating power increases from 226-389 W. The increase in frequency occurs due to the increase in the maximum temperature difference, which comes from the increase in the temperature of the hot side of the stack, T_b. When the temperature T_h, gets higher, the speed of

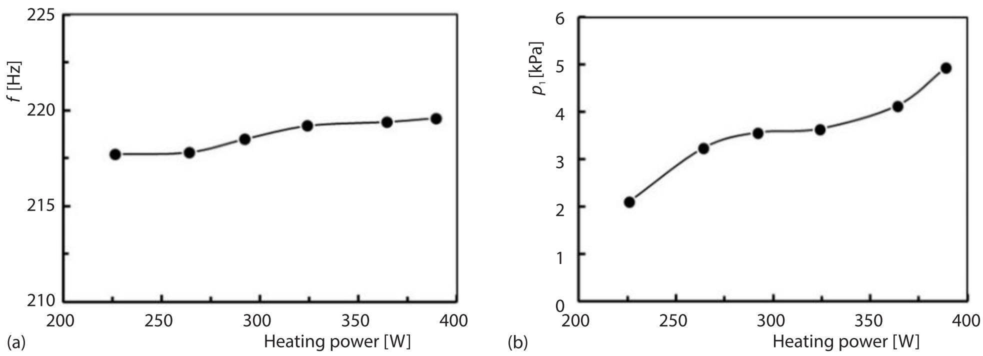

Figure 8. (a) Heating power *vs.* f and (b) heating power *vs.* p_1

sound increases in the gas. As a result, the sound frequency increases because the frequency f is proportional to the sound speed.

Figure 8(b) shows that the amplitude of the generated sound wave pressure p_1, increases significantly as the heating power rises. It increases by around 2.1 Hz, from 217.7-219.6 Hz, when the heating power increases from 226-389 W. That is, around 2.34 times, from 2.10-4.93 kPa, along with the increase in heating power from 226-389 W. Therefore, the sound generated becomes stronger. Thus, the pressure amplitude becomes high.

Figure 9 shows the dependence of the output electrical power produced by a thermoacoustic device on the heating power provided to the thermoacoustic device. It shows that the output electrical power increases almost linearly with the increase in heating power, with a very significant increase from 8.3-32.7 mW (about four times) when the heating power increases from 226-389 W. The increase in output electrical power is caused by an increase in the onset temperature difference ΔT_{onset}, and pressure amplitude, which increases when heating power goes up. The electric power resulting in this investigation can be used for electronic applications, such as prescaler. This electronic device consumes 30 mW of electric power [34].

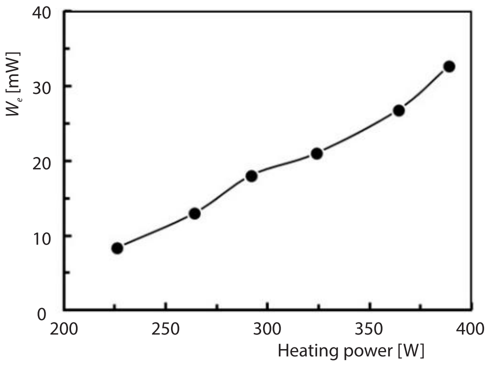

Figure 9. Heating power *vs.* W_e

Conclusions

This study constructs a standing wave-type electricity generator with different heating power configurations. From the study results, the conclusions care as follows.

- When the heating power is 389 W, the highest electric power can be achieved (33 mW). It can be seen clearly that the heating power has an impact on it. The higher heating power was achieved, the higher electric power would be obtained. The electric power of 33 mW can be applied to electronic counting circuit, such as prescaler.
- By changing the heating power, the difference in onset heating temperature increased, meaning that low heating power is preferable for low grade waste heat recovery.
- There is a trade-off between the dependence of electric power on heating power and those of onset heating temperature difference.
- For low grade waste heat recovery applications, the onset heating temperature difference and the electric power should be increased. Therefore, some parameters and working operation should be optimized for future work. Moreover, it is also essential that the geometry or the configuration of the thermoacoustic-electric generator should be investigated deeply to find the high electric power, best performance, and low heating temperature simultaneously.

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